POST-AGB STARS IN GLOBULAR CLUSTERS AND GALACTIC HALOS

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Abstract

We discuss three aspects of post-AGB (PAGB) stars in old populations. (1) *HST* photometry of the nucleus of the planetary nebula (PN) K 648 in the globular cluster (GC) M15 implies a mass of $0.60\,M_\odot$, in contrast to the mean masses of white dwarfs in GCs of $\sim 0.5\,M_\odot$. This suggests that K 648 is descended from a merged binary, and we infer that single Pop II stars do not produce visible PNe. (2) Yellow PAGB stars are the visually brightest stars in old populations ($M_V \simeq -3.3$) and are easily recognizable because of their large Balmer jumps; thus they show great promise as a Pop II standard candle. Two yellow PAGB stars in the GC NGC 5986 have the same V magnitudes to within ± 0.05 mag, supporting an expected narrow luminosity function. (3) Using CCD photometry and a u filter lying below the Balmer jump, we have detected yellow PAGB stars in the halo of M31 and in its dwarf elliptical companion NGC 205. With the Milky Way zero point, we reproduce the Cepheid distance to M31, and find that NGC 205 is $\sim$100 kpc further away than M31. The star counts imply a yellow PAGB lifetime of about 25,000 yr, and their luminosities imply masses near $0.53\,M_\odot$.

1. INTRODUCTION

In this paper we will discuss several aspects of post-AGB (PAGB) stars in old stellar systems, in particular those in globular clusters (GCs) and in the halos of the Milky Way and other galaxies.

Specifically, we will discuss observations with the *Hubble Space Telescope* (*HST*) of the planetary nebula in the GC M15, ground-based observations of two PAGB stars in the GC NGC 5986, and ground-based searches for PAGB stars in the halos of nearby galaxies and their possible application as standard candles for measuring extragalactic distances.

2. K 648 IN M15

Since this work has now been published in detail (Alves, Bond, & Livio 2000), we give only a fairly brief summary here.

Küstner 648 in M15 is one of just four planetary nebulae (PNe) known in Galactic GCs. It was the first to be found (Pease 1928), and it was more than six decades before the other three were discovered: in M22 (Gillett et al. 1989) and Pal 6 and NGC 6441 (Jacoby et al. 1997). As Jacoby et al. point out, this number is lower than expected if every star now evolving in a GC makes a PN.

There are several lines of argument that PAGB evolution in GCs is slow compared to the timescale for dissipation of a PN into space following its ejection at the tip of the AGB. First, recent *HST* detections of white dwarfs in nearby GCs (Renzini et al. 1996; Cool, Piotto, & King 1996; Richer et al. 1997) indicate that the remnant masses are very low ($0.50 \pm 0.02\,M_{\odot}$; see Alves et al. 2000 for details). PAGB stars of masses $\lesssim 0.55 M_{\odot}$—the lowest for which calculations have been made—already have theoretical evolutionary timescales that are much longer than the dissipation timescale for PNe (Schönberner 1983; Vassiliadis & Wood 1994), and the timescales should be even longer at masses of $\sim$$0.5\,M_{\odot}$. In support of this expectation, star counts of PAGB stars in the M31 halo (see below) indicate quite long lifetimes for the portion of the post-AGB evolution from effective temperatures of 5,000 to 10,000 K. It is thus unlikely that typical halo stars will ever be able to ionize visible PNe.

The question then shifts from "Why are there so few PNe in GCs?" to "Why are there *any* PNe at all?". Jacoby et al. (1997) proposed that the observed GC PNe were formed through close-binary interactions, although they did not propose any specific mechanisms.

In order to test this hypothesis, we obtained observations of K 648 and its central star with *HST* and its WFPC2 over an interval of 7 days, in order to search for variations in the brightness of the nucleus due to heating effects in a close binary system. As discussed in our paper, we did not find any variations, and thus have no direct evidence that the nucleus is at present a close binary.

However, the argument can be pressed further by considering the luminosity of the central star. By combining our accurate measurement of the star's V magnitude with its known effective temperature ($40,000 \pm 3,000$ K, based on spectroscopic observations cited in our paper), we find $\log(L/L_\odot) = 3.74 \pm 0.08$. We can now compare its position in the HR diagram with theoretical PAGB tracks, as shown in Fig. 1.

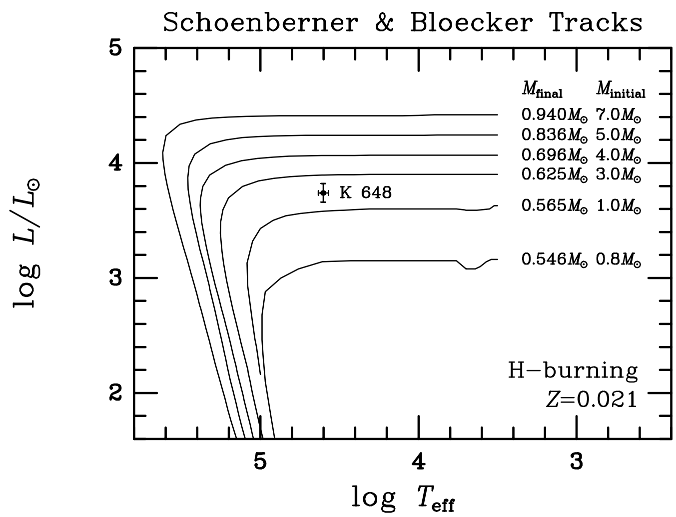

Figure 1 Position of central star of K 648 in the HR diagram, compared with theoretical post-AGB tracks of Schönberner (1979, 1983) and Blöcker (1995). The initial and final masses for each track are indicated at the right. The implied mass of the nucleus is $0.60 \pm 0.02\,M_\odot$.

Although the PAGB tracks plotted in Fig. 1 are for solar metallicity, they still illustrate that the mass of the central star of K 648 is significantly above that of the stellar remnants currently evolving in GCs, which, as noted, are about $0.5\,M_\odot$. Vassiliadis & Wood (1994) find a PAGB luminosity/core-mass relation of $L/L_\odot = 56694(M_c/M_\odot - 0.5)$, nearly independent of metallicity, and applicable to both hydrogen- and helium-burning tracks. Using this formula, we find that the mass of the K 648 central star is $0.60 \pm 0.02\,M_\odot$ (the error estimate includes only observational errors, not any errors in the theory).

Since the K 648 central star is more massive than the normal stellar remnants in GCs, we conclude that the progenitor experienced mass augmentation at some point in its prior evolutionary history, most likely from a close-binary interaction. A plausible scenario is one in which a close binary on the main sequence underwent a W UMa-type contact stage, followed by coalescence (at which time it would probably have appeared as a blue straggler in the color-magnitude diagram). The star subsequently evolved as a more massive object than the bulk of the single stars (which have masses $\sim 0.8\,M_\odot$), allowing it to produce a $0.6\,M_\odot$

remnant which evolved rapidly enough to ionize its ejected AGB envelope before the envelope had time to dissipate.

Our detailed study of K 648 supports the hypothesis that all halo PNe, including those in GCs and in the halo field, are descendants of close binaries, and that single stars in old populations do not make PNe.

3. THE POST-AGB A-F STARS IN NGC 5986

This work has now also been published (Alves, Bond, & Onken 2001), so again we will give only a short summary here.

Population II stars evolving off the AGB and passing through spectral types F and A are the visually brightest members of old populations (due to the behavior of the bolometric correction with effective temperature). These stars should have a narrow luminosity function (LF), because essentially a single main-sequence turnoff mass is feeding the PAGB region of the HR diagram. Moreover these "yellow" PAGB stars are easily recognized because of their enormous Balmer jumps. For these reasons (summarized in more detail by Bond 1997), we believe that yellow PAGB stars in old populations show great promise as a new standard candle for measuring extragalactic distances, especially to early-type galaxies that contain no Cepheid variables. A zero-point calibration for the luminosities of Pop II yellow PAGB stars may be set using those in Galactic GCs.

The little-studied southern GC NGC 5986 is remarkable because it contains two candidate A-F type PAGB stars, discovered some years ago during a photographic grism survey (Bond 1977). Cluster membership was confirmed by their radial velocities and by Strömgren photometry showing very low surface gravities. These two stars are potential primary zero-point calibrators for PAGB absolute magnitudes.

We have obtained CCD photometry of NGC 5986, from which we have derived a reddening and distance modulus of $E(B-V) = 0.29 \pm 0.02$ and $(m-M)_0 = 15.15 \pm 0.10$, respectively (see Alves et al. 2001 for details). The two yellow PAGB stars have the same V magnitudes to within ± 0.05 mag, confirming the expectation of a very narrow LF and supporting the idea that they may constitute a useful new standard candle. By including also the absolute magnitude of the bright A-type star ROA 24 in the GC ω Cen (González & Wallerstein 1992), we find a mean $M_V(\mathrm{PAGB}) = -3.28 \pm 0.07$. Fig. 2 shows the locations of the two PAGB stars in the color-magnitude diagram (CMD) of NGC 5986.

We now have underway a CCD survey of about 100 Galactic GCs, using our new $uBVI$ photometric system (see below), in order to find more examples of yellow PAGB stars and strengthen the zero-point determination.

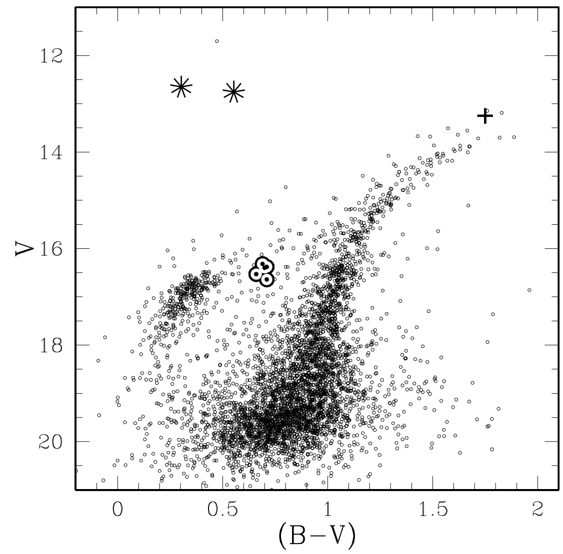

Figure 2 CMD of NGC 5986, from Alves, Bond, & Onken (2001). The cluster's two PAGB stars are shown as asterisks; they are the brightest stars in the cluster, with absolute magnitudes near $M_V = -3.3$. Also marked with circled dots are the cluster's RR Lyrae variables, some 4 mag fainter than the PAGB stars.

4. YELLOW PAGB STARS IN HALOS OF LOCAL GROUP GALAXIES

As described above, yellow PAGB stars show promise as a standard candle, and are easily detectable using a photometric system that is sensitive to their large Balmer jumps. We have been developing a new CCD photometric system that combines the Gunn u filter (lying almost entirely below the Balmer jump) with the standard Johnson-Kron-Cousins BVI bandpasses.

In a preliminary analysis of frames taken in the halo of M31, Bond and Laura Fullton have discovered a sequence of stars with $0 < (B-V) < 0.5$ and large $u - B$ color indices, which are strong candidates for PAGB stars belonging to M31. Their mean V is 20.88 ± 0.06. If we use the preliminary zero-point of $M_V = -3.3$ based on NGC 5986 and ω Cen, as outlined above, we obtain an M31 distance modulus of $(m-M)_V = 24.2$, in reasonably good agreement with that based on Cepheids and other indicators, but requiring only about an hour of 4-m telescope time!

Bond & Fullton (1997) have also obtained $uBVI$ frames of NGC 205, a dwarf elliptical companion of M31. Here we find a sequence of yellow PAGB stars some 0.35 mag fainter than those belonging to the superposed halo of M31, suggesting that NGC 205 is ∼100 kpc further away than M31 itself (in fair agreement with distances from PNe and RR Lyrae variables, although these observations have somewhat greater uncertainties due to the small number of PNe in NGC 205 and the faintness of the RR Lyr stars).

The star counts in the M31 halo fields imply a PAGB lifetime of ∼25,000 yr (for the portion of the evolution from $B - V = 0.5$ to 0.0 only), confirming as noted in our comments on K 648 that PAGB evolution is extremely leisurely in old populations. The luminosities of the M31 PAGB candidates imply a mean mass of $\sim 0.53 M_{\odot}$, in reasonable agreement with the masses inferred for white dwarfs in old populations.

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